

Astrophysics with High Energy Gamma Rays

Heinrich J. Völk

Max-Planck-Institut für Kernphysik, Saupfercheckweg 1,
D-69117 Heidelberg, Germany

Abstract. Recent results, the present status and the perspectives of high energy gamma-ray astronomy are described. Since the satellite observations by the Compton Gamma Ray Observatory and its precursor missions have been reviewed extensively, emphasis is on the results from the ground-based gamma-ray telescopes. They concern the physics of Pulsar Nebulae, Supernova Remnants in their assumed role as the Galactic sources of Cosmic Rays, Jets from Active Galactic Nuclei, and the Extragalactic Background radiation field due to stars and dust in galaxies. Since the gamma-ray emission is nonthermal, this kind of astronomy deals with the pervasive high-energy nonequilibrium states in the Universe. The present build-up of larger and more sensitive instruments, both on the ground and in space, gives fascinating prospects also for observational cosmology and astroparticle physics. Through realistically possible further observational developments at high mountain altitudes a rapid extension of the field is to be expected.

1 Introduction

There is a general consensus that the main energy sources for high energy γ -ray emission are extreme objects in the Universe with high energy turnover. This belief stems from the observation of young Pulsars, Supernova Remnants (SNRs) and Active Galactic Nuclei (AGNs), and we shall discuss some of these detections here.

We know that high energy γ -rays are abundantly produced in collisions of charged particles that have been accelerated in collective processes. They involve ionized systems (i.e. collisionless plasmas), large scale mass motions, and electromagnetic fields. The nonthermal processes are important because they are part of the major energy dissipation processes like shock waves that arise in explosive events, at the breaking of supersonic flows in the form of winds and jets from galaxies, and during mergers of galaxies and clusters. Another important source of particle acceleration should be the dissipative angular momentum transport in magnetized accretion flows near compact objects. Therefore we can plausibly assume that a major fraction of the random kinetic energy in the Universe is nonthermal, with many of the particles at ultrarelativistic energies. And we can see them in gamma rays.

High energy γ -rays might also be due to rare decays of ultra-heavy particles or arise from annihilations of the lightest supersymmetric particles that are widely believed to make up the nonbaryonic Dark Matter. Such indirect identifications with the aid of γ -ray observations are goals of astroparticle physics, even though

no effects have been found until now. All γ -ray detectors include nevertheless the fundamental issue of Dark Matter search as part of their observation programs.

Physically speaking, the most interesting γ -ray features are *localized* emissions. They should immediately portray the generating energetic processes and thus give us new insights into the astrophysics of the sources. Localized emissions from deep gravitational potential wells like the center of our Galaxy also appear as the most promising indicators for accumulations of weakly interacting massive cold Dark Matter particles (WIMPs).

From the point of view of Cosmic Ray (CR) physics γ -ray astronomy is an indirect form of energetic particle detection. But it is a crucial one since even ultrarelativistic charged particles are strongly deflected from straight line orbits by the interstellar and intergalactic magnetic fields. The direct detection of the charged particles will therefore not help us to find their sources even if they happen to reach the Earth. A possible exception are the CRs with the highest energies $\sim 10^{20}$ eV (see the paper by A.A. Watson in these Proceedings). At the much lower energies $\leq 10^{15}$ eV, where energetic particle distributions typically contain almost all their energy *density*, only neutral secondary collision products like γ -rays or neutrinos point back to the sources. Due to their different production modes and their vastly different interaction strength with matter they should give complementary results. Intensive R&D efforts are presently made to develop neutrino astronomy, using large volumes of polar ice and ocean water, as discussed by F. Halzen in these Proceedings. I shall concentrate here on high energy γ -ray astronomy.

Since space born γ -ray astronomy has been reviewed extensively in the past (e.g. [56]), I will put more emphasis the recent results from ground-based telescopes and their impact on major physics questions. The astronomical objects that have been successfully studied are as diverse as Pulsar Nebulae, Supernova Remnants, AGN jets, and the diffuse Extragalactic background radiation field in the Optical/Infrared wavelength range. At the end I will indicate the perspectives of the overall field for the future.

2 High Energy γ -ray Detectors

High energy γ -rays are measured with pair production detectors. They have been used on satellites up to energies of the order of 10 GeV and on the ground above a threshold of about 200 GeV, with special detector arrangements reaching energies as low as 50 GeV.

A typical space instrument is shown in Fig. 1. To reject the dominant flux of charged CR particles, the detector is covered by an anti-coincidence shield. Following the NASA telescope SAS-II, ESA's Cos B was a remarkably long-lived mission, to be finally succeeded by the EGRET-instrument on CGRO. These detectors had a large field of view ~ 1 sr and a small effective area < 1 m², for energies $30 \text{ MeV} \leq E \leq 30 \text{ GeV}$ (e.g. [56]). Since the termination of CGRO no satellite experiment is operating in this energy range.



Fig. 1. (Left) The EGRET instrument on the Compton Gamma Ray Observatory (CGRO). Left: overall instrument with anti-coincidence shield. Right: schematic of conversion of the incoming primary γ -ray into an e^+e^- pair that is tracked in a spark chamber, with energy measurement in the calorimeter on the bottom

Fig. 2. (Right) The 10 m Whipple telescope in Arizona, of the now VERITAS collaboration. The Alt/Azimuth reflector consists of tessellated glass mirrors that focus the atmospheric Cherenkov light onto a camera whose pixels are fast phototubes

At γ -ray energies above about 5 GeV, the atmospheric shower containing many pairs can be used on the ground to detect the associated Cherenkov light. Today the standard instruments are imaging optical telescopes (Fig. 2). Thus the atmosphere itself is part of the detector. The dominant background of showers from nuclear CRs can be suppressed by analysis of the shower images, separating the broad hadronic showers from the concentrated electromagnetic γ -ray - showers. Actually this is best achieved with a stereoscopic array of Cherenkov telescopes, as pioneered by the HEGRA telescope system on La Palma¹. Presently, four major instruments of this type are operating: Whipple/VERITAS (Arizona)², CANGAROO (Australia)³, CAT (French Pyrenees)⁴, and HEGRA.

In contrast to the satellite detectors they have a small field of view of a few degrees and a low duty cycle $\sim 10\%$ due to the restriction to clear and moonless nights. However the effective telescope area $\sim \text{few} \times 10^4 \text{m}^2$ is extremely large, the energy resolution achieved is $\sim 15\%$, and the angular resolution with $\sim 0.1^\circ$ per event is an order of magnitude better than the satellite telescopes flown up to now. Also non-imaging detector systems, using large mirror areas from solar

¹ <http://www.mpi-hd.mpg.de/hfm/CT/CT.html>.

² <http://veritas.sao.arizona.edu/veritas/technical-details.shtml>.

³ <http://icrhp9.icrr.u-tokyo.ac.jp/>.

⁴ <http://lpp90.in2p3.fr/cat/index.html>.

power plants, are being developed to observe at lower thresholds ~ 20 GeV, like CELESTE⁵, STACEE⁶, or GRAAL⁷, but we do not have space to discuss them here.

Space and/or Ground?

As a result of these technological developments the two types of instruments are not only complementary in their energy range but also in their instrumental capabilities. It is therefore no surprise that next generation instruments are developed both for the ground as well as for space. The costs differ by more than an order of magnitude.

3 Gamma-Ray Astrophysics Results at High Energies

Pulsar Nebulae of Rotating Neutron Stars and their Magnetic Fields

Pulsed GeV γ -rays have been detected from eight young Pulsars by EGRET. This emission is usually attributed to radiation from electron - photon cascades in the Pulsar magnetosphere (e.g. [55]), even though recently an alternative radiation mechanism has been proposed due to magnetic reconnection in the winds of Pulsars with streams of alternating magnetic polarity [38].

Unpulsed soft X-ray synchrotron emission from quite a number of extended nebulae around Pulsars has been detected with the ROSAT and ASCA telescopes (e.g [15]), [35]) at rather high luminosities: $L_X \sim 10^{-3} L_{\text{spin-down}}$. Except for the Crab Nebula and PSR B1706 - 44 the implied Inverse Compton (IC) TeV γ -ray emission by the same electrons in the Cosmic Microwave Background (CMB) is only marginally measurable from most sources at present. Yet the coming generation of γ -ray telescopes should be able to detect a significant number of these objects – and therefore the average B-field – because the radiant luminosities should be comparable, $L(E_{\text{IC}}/L(E_{\text{syn}}) = U_{\text{ph}}/U_{\text{B}} \leq 10^{-1}$ for interstellar-type magnetic fields $B \sim 10^{-5} \text{G} = B_{-5}$ which might be typical for many sources [4]; here U_{ph} and U_{B} denote the energy densities of the photon field and the magnetic field, respectively. For the Crab Pulsar, and therefore presumably for other Pulsars as well, the Nebula is thought to arise through an ultrarelativistic wind of e^+e^- pairs, dissipating at a termination shock and accelerating particles that populate a slowly expanding hot and partially nonthermal bubble [52], [36], [13]. The spectrum of the emitted radiation has been modeled phenomenologically by e.g. [27] and [14]. For the Crab Nebula almost the entire energy loss of the rotating neutron star is emitted by synchrotron radiation from the Nebula, that means, in a nonthermal form (Fig. 3)⁸. This picture is of course quite simplified

⁵ <http://www.cenbg/extra/Astroparticule/celeste/index.html>.

⁶ <http://www.astro.ucla.edu/stacee/>.

⁷ <http://rplaga.tripod.com/almeria/>.

⁸ There is in fact no sign for synchrotron emission from a ‘thermal’ shocked wind component with a characteristic energy scale expected in UV/soft X-rays, in possible contrast to the Vela Pulsar (S. Bogovalov, private communication). Using an argu-

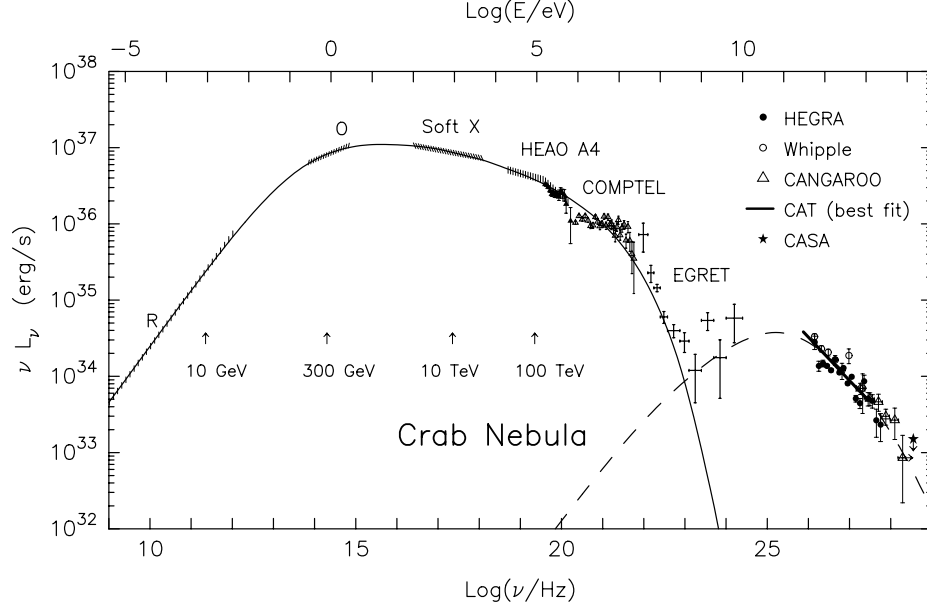


Fig. 3. Spectral energy density νL_ν of the Crab Nebula's emission. The high intensity synchrotron emission reaches into the γ -ray range as observed by several satellite instruments. For this specific young object it exceeds by far the flux in the second hump, presumably due to inverse Compton radiation, as observed with several Cherenkov telescopes (after [14])

as the recent highly resolved X-ray observations of the Crab with the Chandra telescope (<http://chandra.harvard.edu/photo/0052/index.html>) show. But the basic physics ingredients of the Rees & Gunn model seem remarkably robust.

In the very young Crab Nebula $L(E_{\text{IC}}/L(E_{\text{syn}})) \sim 10^{-3}$ which implies a high average magnetic field strength $B \simeq 3 \times 10^{-4}$ Gauss. Thus, despite the fact that it is the strongest steady source of nonthermal radiation in the sky – in particular also in TeV γ -rays – it is a comparatively inefficient IC emitter due to its enormous intrinsic field $B \gg B_{-5}$. Even though magnetic field strengths of this magnitude are expected from equipartition arguments for this object, and had been inferred from the spectral steepening of the synchrotron emission in the far infrared wavelength range [44], the independent measurements of the synchrotron as well as the IC emission, put such inferences on a solid experimental basis.

ment from diffusive shock acceleration theory we speculate that in the extremely luminous Crab Nebula the nonlinear backreaction of the accelerated particles on the flow has smoothed the shock completely, so that the ‘thermal’ component is only adiabatically compressed wind, remaining essentially ‘cold’ (e.g. [30]).

For the second case, PSR B1706 - 44, the steady IC flux is about 1/5 of the Crab flux at TeV energies. However, this does not mean a huge synchrotron luminosity by analogy. Rather we have $L(E_{IC})/L(E_{syn}) \sim 10$, according to [37], [26]. Thus, either the B-field in the Nebula is on average extremely small, as in an old extended bubble, or the particles IC scatter outside the Nebula where the field is probably indeed very low. Large scale morphological information may be needed to interpret the measurement [4].

What can we expect from future γ -ray measurements of a large sample for an improved understanding of Pulsar Nebulae?

If PSR B1706 - 44 turned out to be the more typical case than the Crab Nebula, then we might have a modified picture: In analogy to the lack of equilibrium of nonrelativistic wind bubbles around massive stars (e.g. [22]), the Pulsar Nebula would likely be dynamically unstable allowing the bubble to cool, not in the form of synchrotron cooling but rather by escape of the relativistic particle component into the surrounding diffuse Supernova Remnant. The spatially integrated *total* nonthermal emission should still be comparable to the spin-down luminosity, with the changing magnetic field now playing primarily the role of a wind and particle accelerator and not that of a cooling agent.

The possible appearance of a shocked thermal component of the nebula is expected to exhibit characteristic synchrotron and IC signatures that would directly allow a measurement of the Lorentz factor of the Pulsar Wind. The relative strength of the thermal component may in addition be a indicator for the degree of nonlinearity of the acceleration process.

Shell Type Supernova Remnants and the Origin of Galactic Cosmic Rays

If we disregard the possible compact remnant, the physics interest in diffuse, shell-type Supernova Remnants (SNRs) is readily enumerated: as an ensemble the SNRs lead to the largest mechanical energy input into the Interstellar Medium of galaxies. The strong blast wave from the explosion, sweeping up the circumstellar medium, suggests efficient diffusive shock acceleration of charged nuclei to a power law source spectrum roughly $\propto E^{-2}$. Maximum energies should possibly reach 10^{15} eV and the elemental ratios should very roughly correspond to cosmic abundances. In short, SNRs are suspected to be the sources of the Galactic CRs. Essentially by default.

Even SNRs fulfill the enormous energy requirement for the replenishment of the Cosmic Rays in the Galaxy of $\sim 10^{40}$ erg/yr not by a large margin; at least 10% of the entire mechanical energy released in the event must on average be converted into nonthermal energy of relativistic nuclei.

The only experimental test of this widespread belief consists in direct multi-wavelength observations of SNRs. Due to the inferred hard source spectra, with about equal energy per decade, the best test uses very high energy γ -rays and/or neutrinos since all background radiations fall off more steeply with particle energy. Up to now the required sensitivity can only be approached by

γ -ray experiments and this prospect has been one of the driving forces behind the development of high energy γ -ray astronomy. Notwithstanding these goals, all γ -ray detectors operating up to now have been only marginally sensitive in the face of existing flux estimates [31], [47].

Also CR electrons are detected on the top of the atmosphere, at a 1 percent flux level in comparison with CR nuclei. And they are equally assumed to be accelerated in SNRs.

Although electrons contribute only to a negligible degree to the CR energy density, a high energy electrons emits synchrotron radiation as well as IC γ -rays very efficiently compared with the production rate of π^0 -decay γ -rays per CR nucleus and the overall IC emission can be of the same order of magnitude as the hadronic γ -ray emission from SNRs [45]. In fact, nonthermal electron synchrotron emission has been inferred for a number of SNRs not only at radio wavelengths but also in hard X-rays, and in recent years several such sources have also been reported in TeV γ -rays. It was therefore as simple as it was tempting to interpret them in terms of IC emission alone.

Theoretical Estimates of γ -ray Emission

From the point of view of CR nucleon origin, the γ -ray emission from electrons in SNRs appears as a curse rather than a blessing, since it requires a separation of hadronic from leptonic γ -rays. On the other hand we may as well turn this fact into an advantage. Estimates of the γ -ray production in SNRs are based on diffusive shock acceleration theory. Although one of the best developed theories in astrophysics, its application to the time-dependent situation of an evolving point explosion in a large scale magnetic field is difficult. In addition, the overall evolution is a highly nonlinear dynamical problem due to the high acceleration efficiency and the backreaction of the accelerated particles on the structure of the shock (e.g. [42]). Thus several sub-processes, like the strength of injection of suprathermal particles into the acceleration process, which cannot be calculated very accurately require observational input. Here the synchrotron channel is important since the proton and electron spectra have the same form for relativistic energies (apart from the trivial radiation losses). In this way also the unknown magnetic field strength is constrained.

The estimated flux values also depend on the character of the progenitor star's evolution such as the mass loss for massive stars, and the type of Supernova explosion, and they depend on the overall Supernova energetics. Purely astronomical parameters, like source distance and ambient gas density are obviously important as well. They can only be determined by comprehensive multi-wavelength observations. And although certain parameter combinations are fixed by the given thermal X-ray luminosity and overall SNR dynamics, the combined uncertainty in the estimated γ -ray flux may reach an order of magnitude. Given the marginal instrumental sensitivity, it is not surprising that there were few detections and many non-detections in the past five years. The history of these observational efforts is quite interesting.

Early Observations: Upper Limits

Early observations (~ 10 hours) of radio-bright SNRs, associated with a number of so-called unidentified EGRET sources, were unsuccessful. This concerned especially the well-known core collapse SNRs γ -Cygni and IC-443. Both the Whipple [23] and HEGRA [63] found only upper limits above a few 100 GeV. Extrapolations from the γ -ray energies > 100 MeV of the EGRET observations to 1 TeV are not necessarily appropriate since the EGRET fluxes might be rather contaminated by Pulsar emissions in that detector's very large field of view, cutting off beyond about 20 GeV. The a priori flux estimates for the π^0 -decay γ -rays just about bracket the experimental upper limits.

Deep Observations of Historical Supernovae

After significantly deeper observations (~ 100 hours) detections were reported by the CANGAROO collaboration [59], [60] for the Type Ia Supernova SN 1006 from the year 1006 AD, the X-ray brightest SNR in the Southern Hemisphere [40] and presumably the result of the deflagration of an accreting White Dwarf in a low density environment, as well as for the X-ray-detected southern SNR RX J1713.7-3946 [46], possibly a core collapse SN in the neighborhood of some dense gas clouds [57]. The HEGRA collaboration [7] announced the detection of Cassiopeia A (Cas A), the youngest Galactic SN from around 1680 AD, and presumably the result of the core collapse of a massive Wolf-Rayet progenitor. Cas A is also the brightest nonthermal radio source in the sky. HEGRA [8] also reported a very low upper limit – at 3 percent of the flux from the Crab Nebula – for Tycho's SNR from 1572 AD, a Type Ia Supernova seen by Tycho Brahe (on whose planetary orbit observations Johannes Kepler based his laws of planetary motions). The total observation time for Cas A was 230 h, the deepest γ -ray measurement at TeV energies made up to know. All four objects had been detected before in the radio continuum and in hard X-rays, where also the latter do presumably contain a significant synchrotron contribution.

SN 1006 has been phenomenologically modeled by many authors as an IC source due to the X-ray synchrotron electrons in the Cosmic Microwave Background (see e.g. [59]). This presupposes a rather small interstellar magnetic field of about $4 \mu\text{G}$ in order to explain the high γ -ray flux, given the synchrotron flux, and then no π^0 -decay γ -ray flux is needed. In the opposite case of a significantly larger magnetic field, a significant hadronic component is required, with a shell-type morphology because of the gas compression at the shock [2].

Based on new data, the CANGAROO collaboration has recently reconsidered its initial IC interpretation of the γ -ray emission from SNR RX J1713.7-3946 [32]. From a comparison of the inferred IC spectrum and expected forms of a hadronic spectrum with the measured γ -ray spectrum it was argued that the γ -ray nature of the object should rather be hadronic. This claim did not remain uncontested, based on multi-wavelength arguments [53], [25]. In the absence of an overall theoretical model for this poorly understood source, for which is not clear whether it is due to a Type Ia Supernova or due to a core collapse, it is difficult to see how such controversies can be resolved.

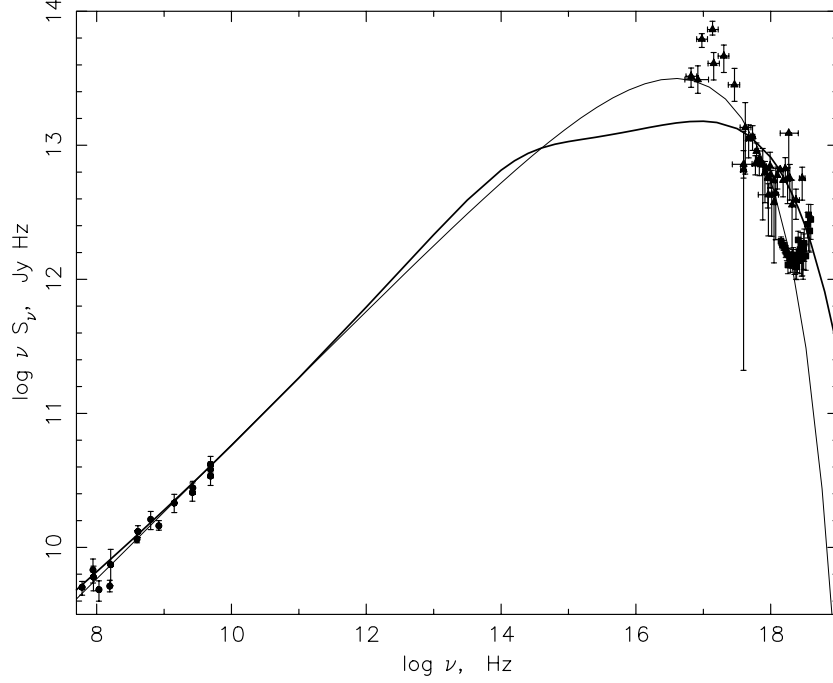


Fig. 4. Theoretical synchrotron spectral energy density for SN 1006 compared with radio and X-ray observations. The best fit is for efficient proton acceleration, an effective upstream magnetic field of 20μ Gauss and an electron to proton ratio $K_{ep} = 1.5 \times 10^{-3}$ (*solid line*). The (physically not plausible) case of inefficient proton acceleration and low field strength of 4μ G (*dashed line*) gives a harder radio spectrum, high nonthermal X-ray emission and $K_{ep} = 4 \times 10^{-2}$ (from [18])

A self consistent estimate for SN 1006, based on time-dependent nonlinear acceleration theory, calculates the space and time evolution of the overall SNR dynamics together with the electron synchrotron, π^0 -decay and IC spectra, with the CMB as primary photon target [16], [17], [18]. It shows (Fig. 4) that not only a high effective magnetic field strength of $\approx 20\mu$ G upstream of the SNR shock is required to describe the overall synchrotron spectrum, from the radio to X-rays [54]; [34]; [12], but that one also needs a strong nonlinear shock modification due to efficient acceleration of nuclei in order to explain the steep radio spectrum. This is consistent with ion injection theory. The theoretical γ -rayspectrum is then dominated by π^0 -decay, even though only by a moderate factor of order 5 (Fig. 5), with the π^0 -decay γ -rayspectrum extending up to almost 100 TeV, and with a dipolar γ -ray emission morphology along the external magnetic field direction. This predicted γ -rayspectrum agrees reasonably well with the EGRET upper limits [48] and the latest TeV results [60]. with the π^0 -decay γ -rayspectrum extending up to almost 100 TeV. An artificially assumed low magnetic field, combined with a physically implausible low proton accel-

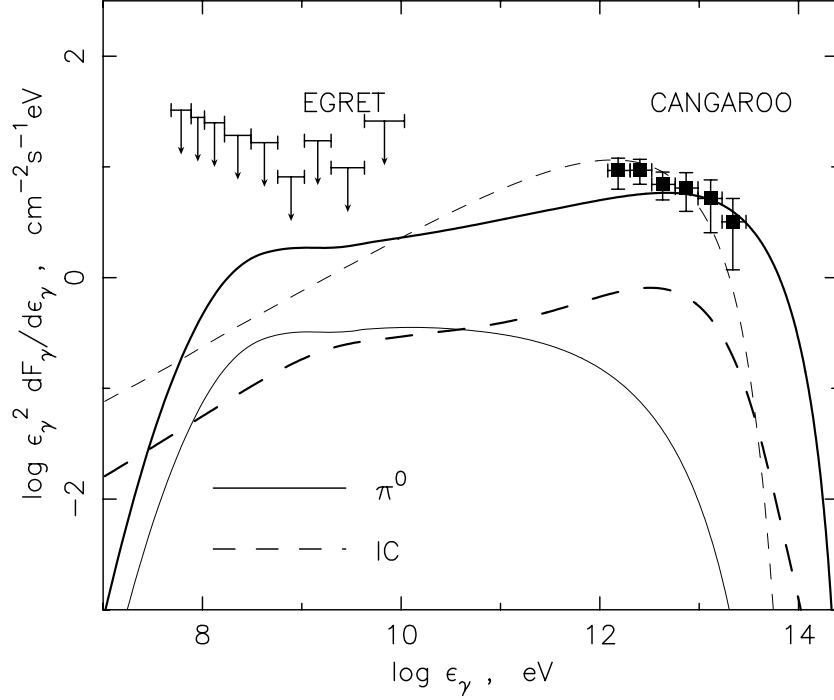


Fig. 5. Theoretical IC (*dashed lines*) and π^0 -decay (*solid lines*) γ -ray spectral energy densities for SN 1006. Efficient proton acceleration is indicated by the thick curves, inefficient proton acceleration by the thin curves. The recent high energy γ -ray flux data and the EGRET upper limits [48] are also shown (from [18])

ation efficiency, describes the synchrotron observations considerably poorer and the IC γ -ray spectrum reaches less than about 10 TeV. As a consequence, good spatial as well as spectral coverage from a minimum of 100 GeV and preferably even from about 100 MeV up to the highest measurable γ -ray energies is needed to ultimately resolve this issue for the high energy nuclear particles of interest. It is also important that an analogous conclusion can be drawn from the radio/X-ray spectra of Tycho's SNR which is calculated to lie just below the present γ -ray detection limit [64]. Also for Cas A – a more difficult object through its complex mass loss history before the explosion – the theory suggests a hadronic γ -ray emission [19]. Recent work strongly supports this interpretation [20]. It will be one of the important tasks for the coming Northern Hemisphere Cherenkov telescopes to obtain good γ -ray spectra from these sources.

HEGRA Galactic Plane Survey

A limited survey of the Galactic Plane (from longitude 85° to -3°) with the HEGRA system using on average 2.8 hours of integration time per pointing (Fig. 6) yielded only upper limits for suspected individual sources. The scan

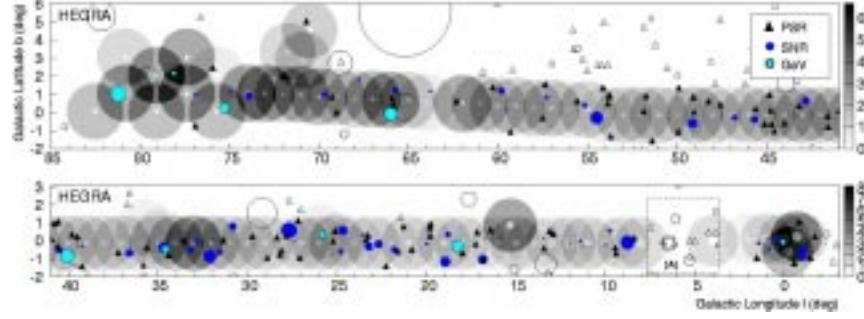


Fig. 6. Observation time in hours (*right ordinate*) used for the individual Galactic plane scan points given by the large *gray circles*. *Filled symbols* correspond to potential sources for which an upper limit is given. *Symbol size* gives the size of the source. Objects in the *dashed box* were not included (from [9])

also included 19 known SNRs. Source stacking of the SNR candidate sources gives a combined upper limit about a factor 2 above the expected π^0 -decay flux [9]. This shows that the nondetections are consistent with a dominant hadronic γ -ray emission.

Conclusions Regarding a SNR Origin for the Galactic Cosmic Rays

The search – under the SNR lamp post – for Galactic CR origin, one of the problems of the century, has made remarkable progress through high energy γ -ray astronomy during the last years. The few detections and the many nondetections are consistent with a SNR origin of the dominant nuclear CR component. We can expect that the new ground-based arrays, coming on line these years, will decide this question.

Blazar Jet Emission

Active Galactic Nuclei (AGNs) are presumably accretion-powered supermassive Black Holes in the center of galaxies. The associated jet-like outflows are often characterized by apparent superluminal motion. Amongst the different AGNs there is a class of objects, the Blazars, which in the optical show a dominant nonthermal continuum together with broad lines, while being highly variable in time. The continuum may be attributed to acceleration processes in the jet (Fig. 7).

Rather unexpectedly about 70 such objects have been found in the GeV region by the EGRET instrument and this was one of the major discoveries of CGRO. The high γ -ray luminosity that dominates the overall spectral energy density distribution from the AGN suggests that the γ -ray emission is strongly Doppler-boosted by coming from a relativistic jet ([21]) whose bulk motion is essentially directed towards the observer. In fact, the apparent luminosity L_{app} is connected with the intrinsic source luminosity L_{int} through $L_{\text{app}} = \delta^4 L_{\text{int}}$, where

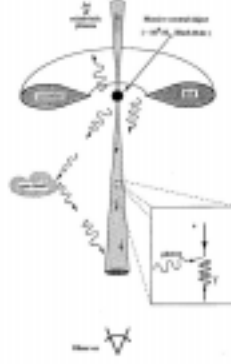


Fig. 7. Schematic of a Blazar. An IC mechanism for the radiation from the bulk relativistic AGN jet is assumed for definiteness, where the ambient photon field may come from various sources, including internal synchrotron photons produced in the jet itself (SSC). For Blazars the jet is pointing close to the line of sight

$\delta = \Gamma^{-1}(1 - \beta \cos\Theta)^{-1} > 1$ is the so-called Doppler factor for bulk motion with Lorentz factor Γ at an angle Θ relative to the line of sight. In the limiting case of Θ going to zero $\delta = 2\Gamma$; δ might well be ~ 10 .

Due to its small detection area the EGRET instrument had long integration times which prevent the analysis of correlations with the fluxes in other wavelength ranges on short time scales. Yet these are especially interesting since the radiative electron cooling times at very high energies are short enough so that their radiation amplitude may follow the dynamical time variations of the system.

In a subclass of Blazars the optical lines are negligible or even absent. These BL Lac objects, named after the prototype galaxy, show the maximum of their synchrotron emission at X-ray energies. The corresponding γ -ray emission is then expected to peak in the TeV region.

Several such objects have indeed been found in the TeV range. And since the effective areas of the ground-based Cherenkov telescopes are very large, they can follow rapid time variations much more effectively than a space detector limited by photon statistics. Due to intergalactic absorption TeV Blazars must be rather nearby at redshifts $z \ll 1$, whereas many of the EGRET AGNs are distant, very luminous Quasars with a flat radio spectrum. It is therefore perhaps not surprising that the number of known TeV Blazars is a factor of 10 smaller. At distances of the order of 150 Mpc, corresponding to the well-measured objects Mkn 421 and Mkn 501 at $z = 0.031$ and $z = 0.034$, respectively, the nonthermal efficiency of such sources can be rather low. In order to avoid intrinsic TeV γ -ray absorption in the radiating jet, δ should typically be of order 10. Requiring the flux to be comparable to the Crab flux for detectability, the intrinsic luminosity has to be roughly equal to $L_{\gamma, \text{intr}}^{\text{source}} \sim (\delta/10)^{-4} \times 10^{40} \text{ erg/sec} \sim 10^{-5} \times L_{\text{Edd}}(10^7 M_{\odot})$,

where $L_{\text{Edd}}(10^7 M_{\odot})$ is the Eddington luminosity of a $10^7 M_{\odot}$ accreting object. The observed variations are fast, down to sub-hour scales that translate to sub-parsec spatial scales of the jet.

The question is then as to the nature of the jet emission. This is first of all an interesting question in itself. Ultimately however, it should also reveal the origin and composition of AGN jets. Presently the γ -ray studies concern the nature of the jet emission and intergalactic absorption.

Nature of the Jet Emission

The two main sources of radiation from jets can be energetic electrons producing IC emission from low energy photon fields, or extremely high energy protons that generate photo-pion and photo-pair cascades or directly radiate synchrotron emission.

At the comparatively low luminosities of BL Lac sources, the most plausible IC target fields for leptonic jets are the radio synchrotron photons from the same population of energetic electrons. The double peaked spectrum typically inferred from quasi-simultaneous X-ray and high energy γ -ray observations (e.g. [61]; Fig. 8) then suggests electron cooling to be about equally distributed between synchrotron and IC losses and fast enough to explain the good temporal correlation observed between the γ -ray with the X-ray fluxes. In such a synchrotron self-Compton (SSC) interpretation the γ -ray flux should increase quadratically with the synchrotron flux. This is about what is observed (see also [41]).

Of course this interpretation is not unique. Alternative hadronic models (e.g [43]) require protons of extremely high energies $\leq 10^{19}$ eV in the jet. They produce pions on the abundant low frequency photon fields longward of far infrared wavelengths, i.e. ultimately a gamma signal and a extremely high energy neutrino signal. Such protons could possibly also be the sources of the ultra-high energy CRs in our Milky Way. And they may possibly power the high energy emission of flat spectrum Quasars that appear optically thick for TeV emission. Unfortunately the cooling of protons on photons is a rather slow process. And for TeV γ -ray sources also a jet optical depth smaller than unity for pair creation is required at TeV energies in order to allow the escape of the photons produced in the interior. This limits the photon density available for proton cooling.

Pion production has to compete with *proton* synchrotron emission which becomes important at such high energies [1]. It is a faster process for BL Lac objects as long as the magnetic field strength in the γ -ray emission region is of order 100 G. Then also essentially all energy goes into TeV γ -rays. As a consequence, at least in the TeV range, hadronic jets favor the proton synchrotron channel. Such very large magnetic fields O(100) G are actually required for the necessary fast acceleration, given the observed fast time variations. Such high B-fields presumably require a massive cold hadronic jet component to ensure dynamical equilibrium.

What are the jets made of?

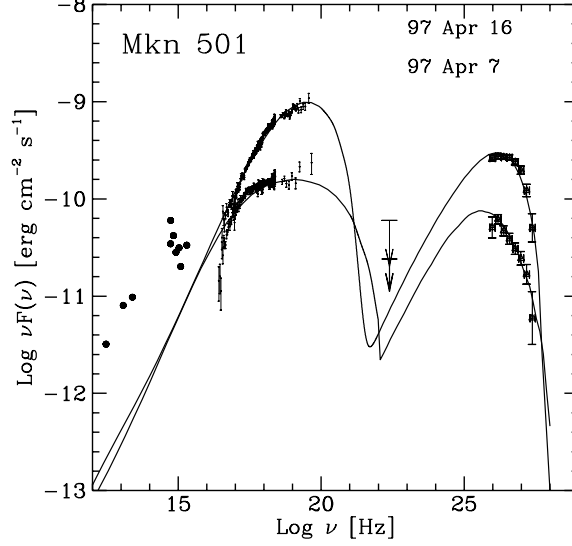


Fig. 8. Multi-wavelength SSC modeling of the X-ray and TeV γ -ray energy fluxes from Mkn 501, observed at different days with the *BeppoSAX* satellite and the CAT telescope, respectively. Upper limits in the 100 MeV region are from EGRET. The Inverse Compton peak lies in the Klein-Nishina domain, with Intergalactic absorption being neglected (from [61])

It is quite surprising that such an extreme alternative has not been resolved until now. Detailed *time-dependent* modeling of simultaneous multi-wavelength observations will be necessary to clearly distinguish between leptonic and hadronic jets in BL Lac objects. Obviously this is at the same time one of the prerequisites for an understanding of the jet origin in the first place.

Intergalactic γ -ray Absorption on the Extragalactic Background Light

The spectrum of the diffuse Extragalactic radiation field has a double peak structure due to the direct radiation from stars and AGNs in the UV, optical and near infrared on the one hand, and the mid and far infrared reradiation of absorbed starlight by dust at longer wavelengths, all integrated over the evolution of the Universe.

In this Extragalactic Background Light (EBL) TeV γ -rays are absorbed by pair production with a cross section that peaks at about one quarter of the Thompson cross section σ_T . Therefore one can approximately relate the two photon energies in the form $(E/1\text{TeV}) \approx (h\nu/1\text{eV})^{-1}$ and write the optical depth in the form $\tau(E) = \xi(\sigma_T/4) h\nu n_{\text{ph}}(h\nu) \times \text{distance}$, where $n_{\text{ph}}(h\nu)$ is the differential number density of the low energy photons and ξ is of order unity. Thus, for a constant spectral energy density of the EBL, $\tau(E)$ increases linearly

with E and the TeV spectra from Extragalactic sources will have an imprint in the form of characteristic absorption features with a high energy cutoff. These absorption features should give information on the spectrum of the EBL in an elegant way, an information that direct observations of the EBL can only yield through a difficult and uncertain subtraction of dominant foreground radiations such as the Zodiacal Light or the so-called Galactic Cirrus; this subtraction is especially problematic in the mid infrared region.

The uncertainty in this method lies in the unknown primary γ -ray source spectrum. Thus for example Mkn 501 shows an exponential cutoff proportional to $E^{-1.9} \exp^{-E/E_0}$, with $E_0 = 6.2$ TeV which is roughly consistent with observational estimates of the EBL spectrum [6]. However, on a 3σ level, the source Mkn 421 (at about the same redshift) appears to have a significantly lower cutoff energy of $E = 3.6$ TeV [11], precluding the possibility of the cutoff being only an absorption feature of the EBL.

Therefore we need to measure γ -ray sources at different, in fact higher distances. Fortunately, the BL Lac object H 1426 + 428 at the fourfold redshift $z = 0.129$ could recently be detected and its TeV spectrum measured by HEGRA is within the errors *consistent with the characteristic absorption features* expected [11]. The source spectrum was assumed to be $\propto E^{-1.92}$, consistent with X-ray synchrotron observations (Fig. 10). The absorption feature consists in a strong hardening of the observed γ -ray spectrum between about 2 and 5 TeV (Fig. 9).

One can also fit a power law to the HEGRA data alone – with no further justification than the simplicity of a 2-parameter straight line – obtaining a somewhat lower overall statistical significance. However, this power law is quite flat and it deviates therefore strongly from a steep absorbed spectrum at energies below 1 TeV. In fact, the Whipple [50] and CAT [29] telescopes have recently confirmed the expected steep spectrum below 1 TeV.

Perspectives for the EBL from γ -ray measurements

These results show clearly that TeV cutoffs alone contain insufficient information, in contrast to earlier expectations [58], because cutoffs can also be mimicked by several effects, foremost by an intrinsic cutoff of the source spectrum due to a finite maximum particle energy, or by the Klein-Nishina effect. On the other hand the characteristic wavelength variation of the absorption characteristics of the γ -ray spectra, measured at different redshifts, offers the prospect of making accurate and convincing γ -ray determinations of the EBL in the near and mid infrared in the near future.

4 Future Perspectives of High Energy γ -ray Astronomy

Physics Questions

With the next generation of instruments coming on line a much larger number of sources will be detected. Such an increase by an order of magnitude gives good reasons to expect that several of the major physics problems which we have discussed here, will be solved. This should become especially true, in one way or

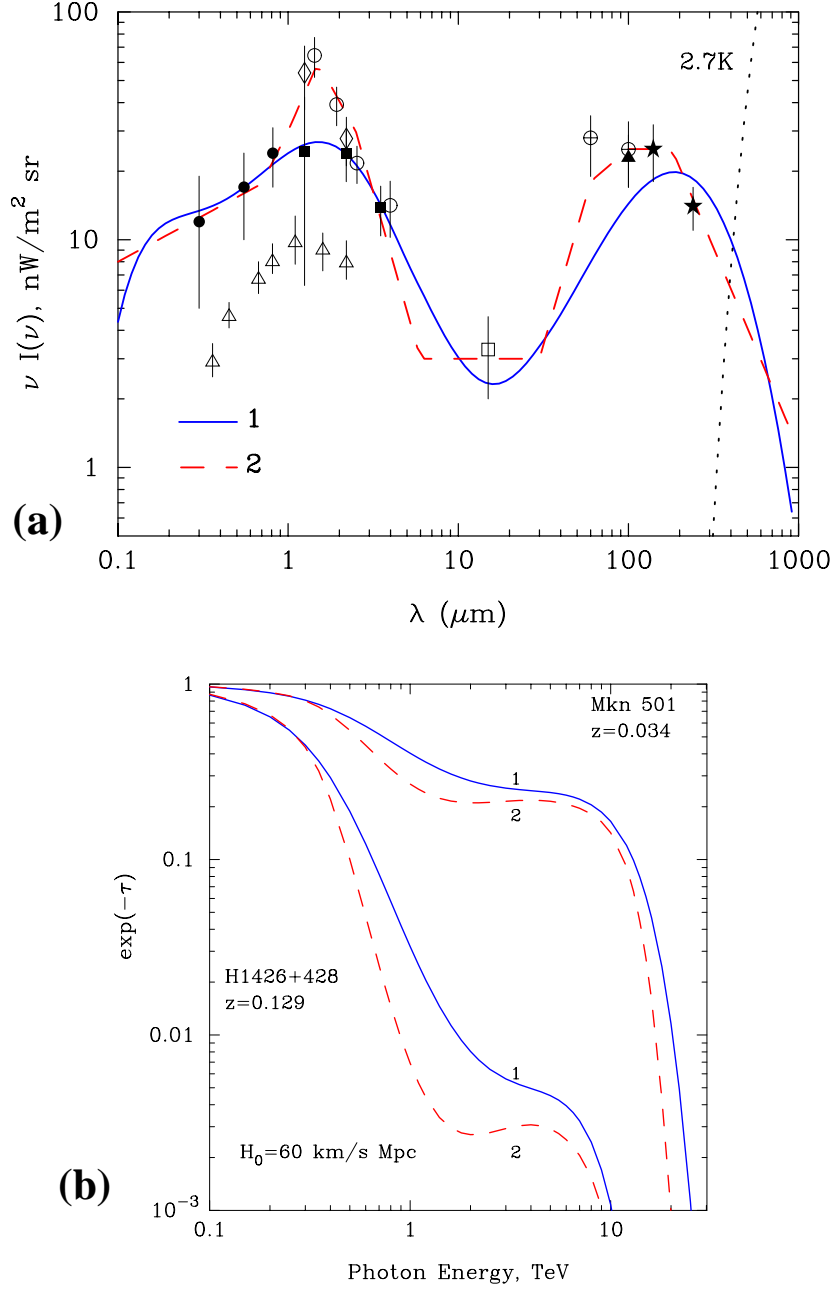


Fig. 9. Different empirical approximations to the direct measurements of the spectral energy density of the EBL (a), and their energy-dependent absorption effect on TeV photons from Mkn 501 and H 1426 + 428, respectively (b). The optical depth is denoted by τ (from [11])

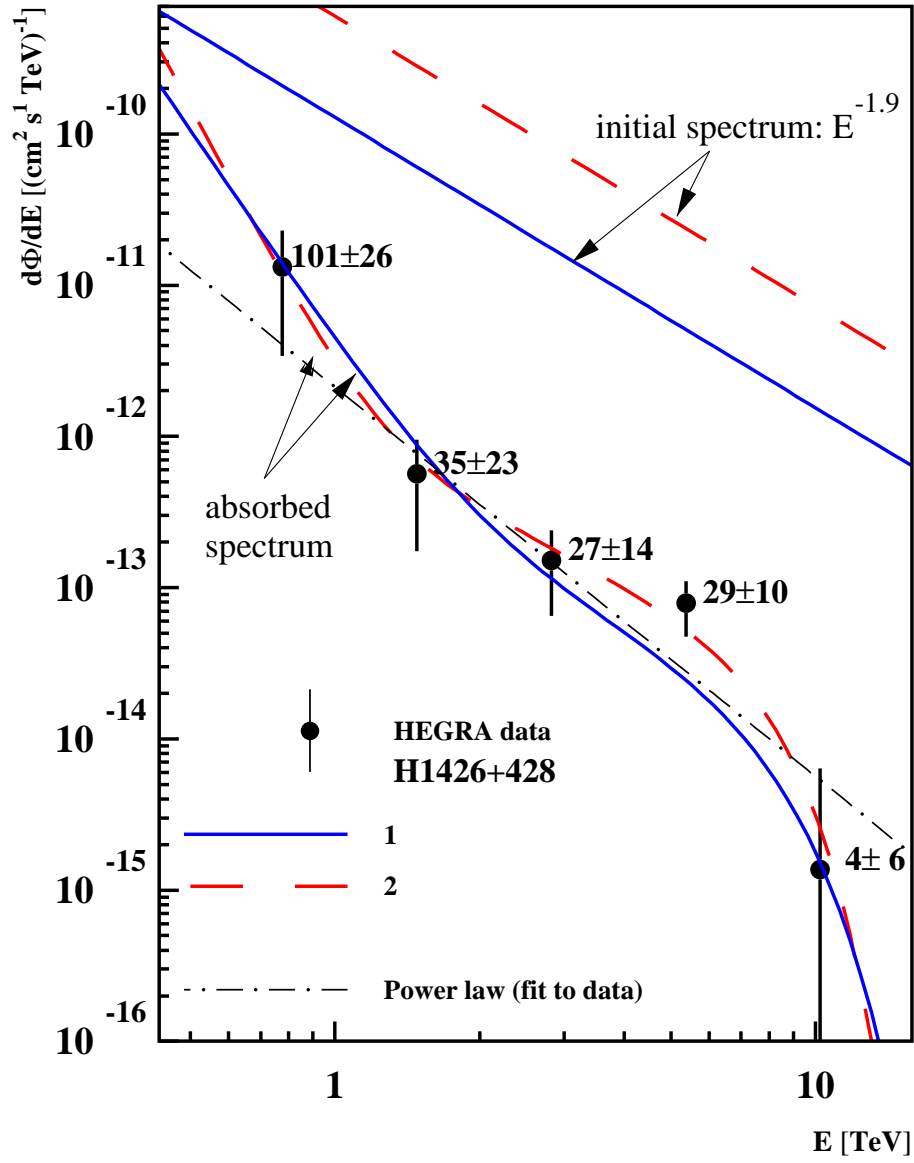


Fig. 10. Differential HEGRA spectrum of H 1426 + 428 and its approximation (*solid* and *dashed* curve) by the absorption effect, cf. Fig. 9, on initial (primary source) spectra $\propto E^{-1.9}$ suggested by X-ray measurements. A power law fit is given by the *dash-dotted* curve (from [11])

the other, for the origin of the Galactic Cosmic Rays from SNRs. Another area of research, not mentioned above at all, will be the 3-dimensional nonthermal structure of the Galaxy, together with its halo in the form of the Galactic Wind (e.g. [51]). It should find its complement in investigations at low radio frequencies with the proposed Square Kilometer Array.

Besides these developments γ -ray astronomy will increasingly move to Extragalactic sources and to observational cosmology and, at least in a serendipitous form, to Astroparticle Physics.

Beyond intrinsic AGN physics, the instrumental sensitivity increase will allow studies of nearby starburst galaxies and through them the expected formation of a strong nonthermal component *throughout the Universe* can be studied. Complementary studies aim at the nonthermal component of galaxy clusters. By its large size and expected turbulent agitation, the Intracluster Medium should not only confine the visible thermal matter and the Dark Matter, but also the relativistic hadronic component since its formation. This means that clusters of galaxies are closed systems, preserving not only the chemical but also the nonthermal history and entropy production since structure formation started [62].

Strong emitters of very high energy γ -rays like the jets from flat spectrum Quasars are expected to be surrounded by a halo of e^+e^- pairs due to the absorption of very high energy γ -rays with $E_\gamma \sim 100$ TeV in the EBL and subsequent magnetic isotropization in an intergalactic field $> 10^{-12}$ G. The Compton upscattering of photons from the Cosmic Microwave Background initiates a cascade that becomes observable at lower γ -ray energies when the space between us and the source becomes ultimately transparent [3]. The halos would be visible even if the jet points in an arbitrary direction relative to the observer due to the magnetic isotropization. Measurements of the angular size $\sim 1^\circ$ and γ -ray energy spectrum of such halos should allow the determination of the Hubble constant, i.e. the *absolute distance* of these objects, and a determination of the *local* (in redshift z) EBL. Even though such measurements promise to be difficult, and although there exists a substantial confusion problem at larger redshifts, the possible rewards are correspondingly high.

It is also worth to emphasize the perspectives for Astroparticle Physics, for instance by γ -ray observations of the Galactic Center region. One set of simulations of the mass density $\rho(r)$ of Cold Dark Matter particles in the gravitational potential well of the Galaxy suggests a rise $\varrho(r) \propto r^{-1}$ with decreasing radius in the innermost region [49]. However, other simulations come to more extreme results (see e.g. [39] for a recent convergence study): $\varrho(r) \propto r^{-3/2}$ for very small r , while agreeing for larger radii with the r^{-1} -dependence. Depending on whether there is a strong density cusp or not, the annihilation rate of e.g. Dark Matter neutralinos $\propto \varrho^2$ in the very Galactic Center could therefore be quite high or rather small (e.g. [24]) and γ -ray observations of the Galactic Center will not only be interesting from an astronomical point of view. Calculations of the neutralino annihilation flux (e.g. [33]) suggest the appearance of a line, possibly at energies between 100 GeV and 1 TeV, besides a continuum that is strongly falling off with

γ -ray energy. Fluxes may be at the percent level of the Crab Nebula. Observations with the coming generation of Cherenkov telescopes could thus provide a test of different halo models of our Galaxy and/or put meaningful constraints on SUSY parameter space.

Next Generation Instruments

The next space projects in high energy γ -ray astronomy will be NASA's Gamma-ray Large Astronomical Space Telescope GLAST⁹ with an expected launch in 2007, and its small brother, the Italian precursor mission Astrorivelatore Gamma ad Immagini LEggero AGILE¹⁰, whose launch is presently foreseen for 2004. Both detectors are based on silicon strip technology. Comparable in sensitivity to EGRET, AGILE will have a much larger FoV of 3 sr and thus be very good for surveys. Similarly, it is largely its survey capability which will distinguish GLAST from ground based Cherenkov telescopes. However, GLAST will also be more than an order of magnitude step beyond EGRET in sensitivity, angular resolution, and spectral coverage. The energy range will extend to hundreds of GeV, even though for reasons of statistics its de facto energy range will usually be limited to some tens of GeV. GLAST will, first of all, be used to investigate the large number of unidentified EGRET sources, left over from the CGRO mission. Beyond, it is expected to find hundreds of AGNs, to localize a fair number of SNRs, and to search for extended Extragalactic objects.

On the ground, in the complementary energy region above ~ 50 GeV, the future has already begun in Australia with the first 10 m Cherenkov telescope of the 2x2 stereoscopic array CANGAROO III¹¹ operating since more than one year. The next telescopes are expected to start observations soon. In Namibia, the first 12 m - telescope of the 2x2 array of the Phase I of the High Energy Stereoscopic System H.E.S.S.¹² became operational this June 2002 (Fig. 11), to be followed by the other three components in time steps of 6 months. The 17 m single MAGIC telescope¹³ is due to be commissioned in La Palma still in 2002. And in a few years the 7-telescope 10 m array VERITAS¹⁴ will follow in Arizona.

Typically these instruments will have an energy threshold around 100 GeV, and an order of magnitude increase in sensitivity at 1 TeV compared to the previous generation instruments with their excellent angular resolution of 0.1° . The energy resolution $\Delta E/E$ is about 15 %. Several of the ground based instruments will have made detailed observations already years before GLAST. Nevertheless the superior survey capability and the lower energy range will still reserve GLAST important and unique goals.

The attraction of γ -ray astronomy at high energies is that it is a young field. Whereas satellite instruments appear limited in their capabilities simply by the

⁹ <http://glast.gsfc.nasa.gov/>.

¹⁰ <http://agile.mi.iasf.cnr.it/Homepage/>.

¹¹ <http://icrhp9.icrr.u-tokyo.ac.jp/c-ii.html>.

¹² <http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html>.

¹³ <http://hegra1.mppmu.mpg.de/MAGICWeb/>.

¹⁴ <http://veritas.sao.arizona.edu/veritas/index/shtml>.



Fig. 11. The first of the four 12 m telescopes of H.E.S.S. Phase I in Namibia. The tessellated mirror consists of 380 aluminized glass mirrors of 60 cm diameter. The focal plane detector (‘camera’) has 960 ultrafast photomultiplier pixels, covering an area of 1.4 m that corresponds to a field of view of 5° . The energy threshold is about 100 GeV and the sensitivity is about 10^{-12} erg/(cm²s) above 100 GeV and about 10^{-13} erg/(cm²s) above 1 TeV for 50 h of observation. (Photograph F. Toussenel, June 2002)

required sizes and masses, this is not really true for ground-based Cherenkov telescopes. Putting them on high mountain altitude, like ESO’s ALMA site at 5000 m a.s.l., a future large extension in threshold down to about 5 GeV is possible with a 2x2 array of 20 m telescopes, while basically retaining the enormous effective area in the 10^5 m² range [5]. As a consequence, close-by γ -ray bright objects like the Vela Pulsar could be detected in seconds with such an array.

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